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Mechanically induced stumbling during human treadmill walking

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Abstract

A new method to study the reactions to unexpected mechanical perturbations during human walking on a treadmill is presented. Perturbations consisted of an obstruction of the forward swinging foot during the early swing phase. These were caused by obstacles which were dropped on the treadmill in front of the subject. The timing of the perturbation was controlled by an electromagnet which released the obstacle at a preprogrammed delay after left or right heel strike. This kind of perturbation evoked stumbling reactions. The electromyographic (EMG) responses during these stumbling reactions had mean latencies of 76 ms in both the ipsilateral biceps femoris and rectus femoris when perturbations were applied in early swing. During the perturbed swing, increased flexion in the knee occurred to lift the foot over the obstacle. Both the EMG and kinesiologic responses were reproducible when perturbations were presented in the same part of the swing phase of different step cycles.

Keywords: Mechanical perturbation; Stumble response; Human walking; Treadmill; EMG; Kinesiology

1. Introduction

Studies on reactions to selective electrical nerve stimulation during human walking have given insight into the way the central nervous system generates reflex responses to either cutaneous (Duysens et al., 1990, 1992; Yang and Stein, 1990) or proprioceptive stimulation (Capaday and Stein, 1986; Brooke et al., 1991). Little is known about the role of these reflex responses in compensatory reactions to more realistic perturbations (e.g., stumbling over unexpected objects). In contrast to electrical stimulation, in realistic perturbations a selective activation of cutaneous or proprioceptive afferents does not occur. Furthermore, these perturbations may be fundamentally different since the balance is disrupted. To achieve this kind of perturbations, unexpected mechanically obstructing stimuli must be applied.

Some studies on unexpected mechanical stimulation during cat locomotion have been reported (Forssberg, 1979; Wand et al., 1980; Drew and Rossignol, 1987; Buford and Smith, 1993). The swing phase was mechanically obstructed by manually positioning rods in front of the paw. The so-called 'stumbling corrective reaction' could be evoked using this method (Forssberg, 1979).

Much less is known about unexpected mechanical perturbations during human locomotion. To perturb the normal walking pattern mechanically, movements of a platform incorporated into the surface of a walkway (Nashner, 1980) and acceleration or deceleration of the treadmill (Berger et al., 1984; Dietz et al., 1984) have been used. Such manipulations allow to study responses to perturbations during the stance phase of walking.

In everyday life, however, perturbations often occur during the swing phase. To simulate such perturbations, in some studies a momentary resistance was applied during the swing phase by a cord which was fixed above the ankle joint of the swinging leg (Garret and Luckwill, 1983; Dietz et al., 1986). The latency between onset of impulse and appearance of electromyographic (EMG) responses in both ipsilateral (tibialis anterior; rectus femoris) and contralateral muscles (gastrocnemius; biceps femoris) was 65–70 ms (Dietz et al., 1986). Different responses occurred depending upon whether the resistance was applied at the onset or at the end of the swing phase.

Naturally, perturbations during the swing phase are often caused by a collision of the *foot* with unexpected obstacles. To achieve this, in a few studies obstacles were unexpectedly raised above the surface of a walkway to

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perturb the walking pattern in the swing phase (Grabiner et al., 1993; Eng et al., 1994). These perturbations were caused at a given specific position on the walkway. Although with this method responses to tripping perturbations could be studied, this method has the disadvantage that subjects know more or less where they can expect the obstacle.

Until now, for humans no method has been developed to obstruct the forward swinging leg during treadmill walking, by causing a collision of the foot with unexpected obstacles. In the method described in the present study, obstacles were dropped on a treadmill to perturb the step cycle at a preprogrammed time. It will be shown that with this method it is possible to reproduce unexpected perturbations and to evoke reproducible stumble responses under controlled laboratory settings.

2. Methods

2.1. Experimental set-up

Bipolar surface EMG activity was recorded in 5 healthy subjects (3 male, 2 female; aged 20–47 years) while walking on a treadmill (Woodway type ERGO EL2; walking surface treadmill belt: length × width = 2.0 × 0.7 m) at 4 km/h. The electrodes were placed over the biceps femoris (BF) and rectus femoris (RF) of the left leg (see also Duysens et al., 1991). Using a laterally placed goniometer, the joint angles of the left knee were measured. Very thin insole footswitches were used to detect foot contact of each leg with the treadmill. In addition, markers were placed on the left shoulder, hip, lateral epicondyl of the femur, fibular head, lateral malleolus, heel, and metatarsal bone I. The movements of the subjects were recorded on video (25 Hz) during the experiment. Stick diagrams of the movements were made on the basis of the recorded marker positions.

The mechanical perturbation of the left leg during the swing phase was produced by an obstacle which was dropped on the treadmill. The obstacle used consisted of a combination of wood, polystyrene foam, and iron. The obstacle had a length, width, and height of 40.0, 30.0, and 4.5 cm, respectively. The obstacle weighed 2.2 kg. This weight was critical since lighter obstacles were too easily kicked away or lifted by the toes, while heavier ones were considered less safe, since a collision could be painful for the toes. The obstacle was held by an electromagnet above the treadmill approximately one meter in front of the subject's left leg (Fig. 1). At a preprogrammed delay after heel strike of the right or the left foot, the computer could trigger the electromagnet to drop the obstacle on the treadmill in front of the left foot. A pressure-sensitive strip (same technique as footswitches), attached to the front of the obstacle, was used to determine the time at which the left foot hit the obstacle.

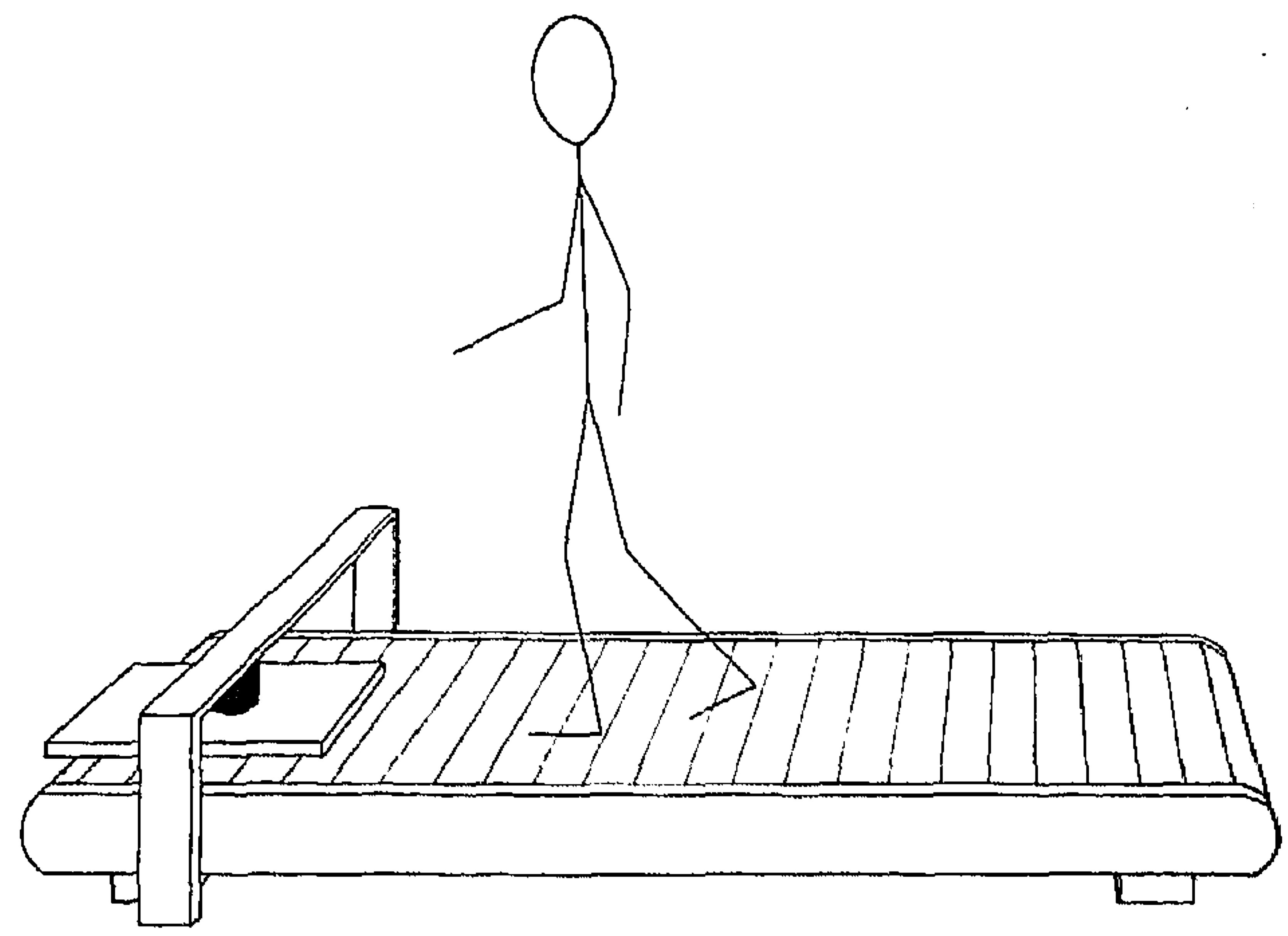

Fig. 1. Schematic diagram of the experimental set-up. The electromagnet is attached to a bridge over the treadmill. It holds the obstacle just above the treadmill surface in front of the subject's left foot. When the electromagnet is switched off after a trigger from the computer (not shown), the obstacle falls on the treadmill. A pressure-sensitive strip on the front side of the obstacle gives a signal to the computer to determine the time of perturbation when the foot of the subject hits the obstacle.

The perturbations were introduced unexpectedly. To prevent that the subjects could hear when the obstacle fell on the treadmill, earplugs were used. In addition, subjects wore headphones through which loud music was played. To prevent the subjects from seeing the approaching obstacle, glasses were used which blocked downward sight. Further, to ensure that the subjects did not feel the vibration of the obstacle landing on the treadmill, the treadmill was struck with a metal rod at irregular intervals.

It was important that the subjects kept the same position on the treadmill during the experiment. Forward or backward shifts would endanger the precise timing of the perturbation with respect to the phase in the step cycle. Shifts to the right could cause the left foot to miss the obstacle and no stumble would occur. Shifts to the left could cause the right foot to touch the obstacle instead of the left foot. In the latter case the subject could anticipate the approaching obstacle and would lift the left leg over the obstacle to avoid stumbling. To help the subjects to maintain the same position, reference lines were applied to the wall and the guard rail of the treadmill which gave the subjects direct visual feedback about their position on the treadmill. During a short period of walking, the subjects were trained to maintain a stable position on the treadmill.

The subjects wore a safety harness that was fixed to a safety brake on the ceiling. In case a subject would start to fall, the safety harness would hold the subject and stop the treadmill. In fact, this never happened since none of the subjects fell. Flexible gymnastic shoes, containing the thin insole footswitches were worn. In the shoe, the toes of the left foot were covered with a piece of cotton to prevent them from getting hurt when the foot struck the wooden front of the obstacle. In addition, a piece of cotton was applied to the heel of the right foot to protect this heel if the obstacle was accidentally kicked towards the right foot.

2.2. Data sampling

Measurements were made during a time interval which started 100 ms prior to the triggering of the electromagnet and continued for 2100 ms. For the control trials, the same intervals were measured, but no obstacle was dropped after the trigger. Because in the actual experiments the delay between the trigger and the time of the collision with the obstacle was maximally 1330 ms, at least 670 ms of data were measured after each perturbation. All signals were stored on hard disk. The on-line inspection of the data was performed on a separate monitor. The EMG signals were amplified, high-pass filtered (> 3 Hz), full-wave rectified, low-pass filtered (< 300 Hz). All data were transferred on-line via an analog-digital converter (sampled at 500 Hz).

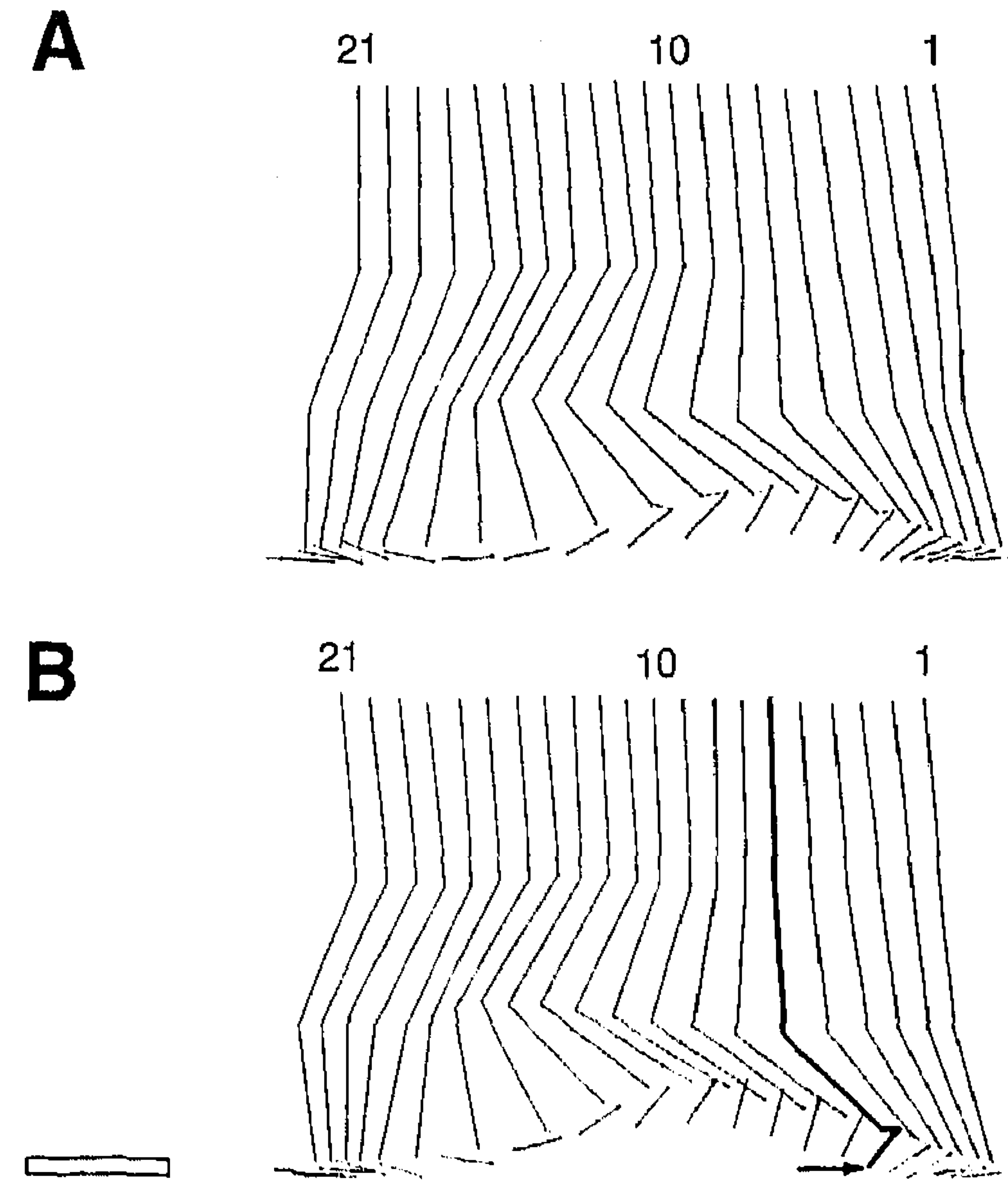

Fig. 2. Stick diagrams of normal swing (A) and stumble response at early swing for an obstacle with a height of 4.5 cm (B). Stick diagrams are reconstructed with intervals of 40 ms and are numbered as phase 1–21. Each stick has been displaced by moving the position of the marker on the shoulder with equal distances forwards (to the left) with respect to a fixed point on the treadmill belt. Arrow indicates the perturbation time at early swing (phase 6 in B). In B the obstacle was initially lifted along with the toe.

3. Results

Successful stumbling was induced in all 5 subjects. During the stumbling reaction the ipsilateral foot was lifted over the obstacle. Although there was enough room to step beside the obstacle (width of obstacle and treadmill belt were 30 and 70 cm, respectively), none of the subjects made such lateral movements. On the basis of the video pictures, stick diagrams were made to illustrate movements during the normal unperturbed (Fig. 2A) and perturbed swing (Fig. 2B). A stumbling response after a perturbation (arrow) in the early swing is shown in Fig. 2B. The obstacle (4.5 cm high) is shown along with the stick diagram. Following the foot contact with the obstacle (in Fig. 2B, phase 6), it can be seen that an extra plantar flexion at the ankle occurred (phase 8). In the unperturbed swing, the maximal observed plantar flexion was smaller (Fig. 2A; phase 10). Approximately 200 ms after the collision of the foot with the obstacle (phase 11), there was a change from plantar to dorsal flexion at the ankle in order to prepare for the landing on the heel. In addition, in the perturbed swing the maximal knee flexion (Fig. 2B; phase 12) increased with respect to the maximal flexion in the normal swing phase (Fig. 2A; phase 11).

Sometimes the obstacle was lifted along with the foot. In those cases the maximum height of foot lifting depended on how high the obstacle was lifted. This is illustrated in Fig. 3. This figure shows an example in which the obstacle is extremely lifted by the foot. After lifting the obstacle along with the foot, the obstacle falls back on the treadmill and the foot is lifted over the obstacle.

To illustrate that the stumble responses were reproducible within subjects, the EMG and joint angle changes (as measured with a goniometer) were compared during the stumble responses of 5 separate trials of perturbation of one subject (Fig. 4). The perturbations were caused during

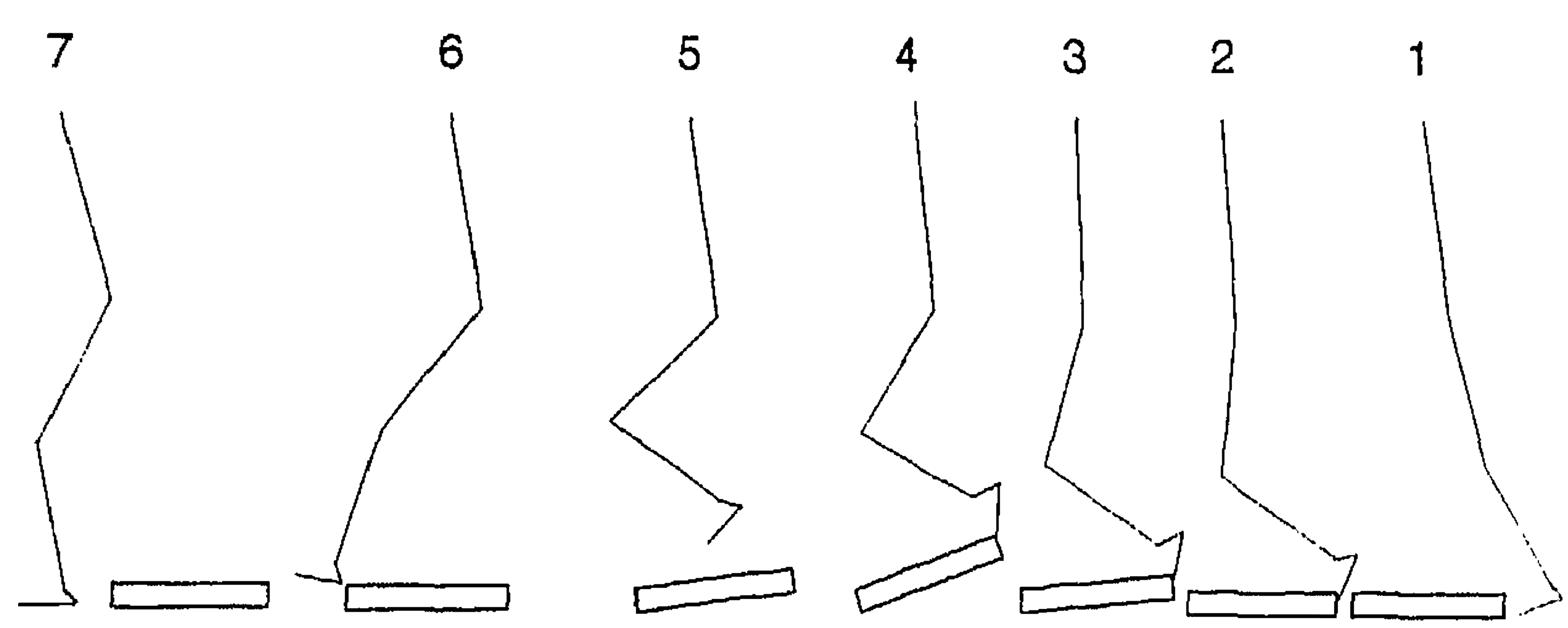

Fig. 3. Schematic example of a trial in which the obstacle was extremely lifted following perturbation. After starting the forward sway (1), the foot hits the obstacle in the early swing phase (2). When the leg flexes, the obstacle is lifted along with the foot (3 and 4). After further flexion, the obstacle is released from the foot and falls back on the treadmill (5 and 6), while the foot moves over the obstacle. Finally, the foot is placed on the treadmill (7).

early swing. In Fig. 4A, the changes in knee joint angle during 5 stumble responses (traces 1–5) were compared with a control trial (lowest trace). In each trial, two periods of flexion could be distinguished. The first deviation from the normal (control) knee joint angle was observed on average 48 ms (SD: 4 ms; $n = 5$) following the perturbation (see single arrow in Fig. 4A). The second extra flexion of the knee was observed with a mean latency of 174 ms (SD: 11 ms; $n = 5$) after the perturbation (see double arrow in Fig. 4A). The knee started to extend on average 396 ms (SD: 17 ms; $n = 5$) after the perturbation.

In each perturbation trial (Fig. 4B), the BF showed a small early response with a latency of 76 ms (SD: 3 ms) and a large response with a latency of 125 ms (SD: 4 ms). The durations of the whole complex of early and late BF responses were also similar for the different trials with a mean duration of 151 ms (SD: 6 ms). In the control trial, the BF showed no activity in this part of the swing phase. The RF showed a small response with a mean latency of 76 ms (SD: 5 ms) after the perturbation (Fig. 4C). The main EMG burst in the RF occurred at a mean latency of 266 ms (SD: 21 ms) with a mean duration of 148 ms (SD: 21 ms).

In short, several periods could be distinguished after a perturbation. In the first period, one can observe passive (no EMG activity) changes in knee joint angle (mean latency: 48 ms) due to a mechanical effect of the obstruction. In the second period the foot is lifted actively over the obstacle in response to the perturbation. Presumably, the large activation of the BF at 125 ms correlated with this knee flexion at 174 ms. Thirdly, the foot placement is prepared by extension of the knee (after $\approx$ 396 ms), aided by knee extensors such as RF (response burst at $\approx$ 266 ms).

In all perturbation trials (Fig. 4), the duration of the swing phase was lengthened as compared to the control trials. The mean durations of the swing in the control trials and the perturbation trials were 488 ms (SD: 14 ms; $n = 10$) and 684 ms (SD: 30 ms; $n = 5$), respectively. Hence the duration of the swing phase increased on average with 196 ms (SD: 14 ms; Welch). The question rose whether the introduction of the perturbation affected the structure of the normal walking pattern (due to fear for stumbling or due to anticipation to the perturbation). The mean duration of the control step cycles during the stumble experiment was 488 ms (SD: 14 ms; $n = 10$) for the

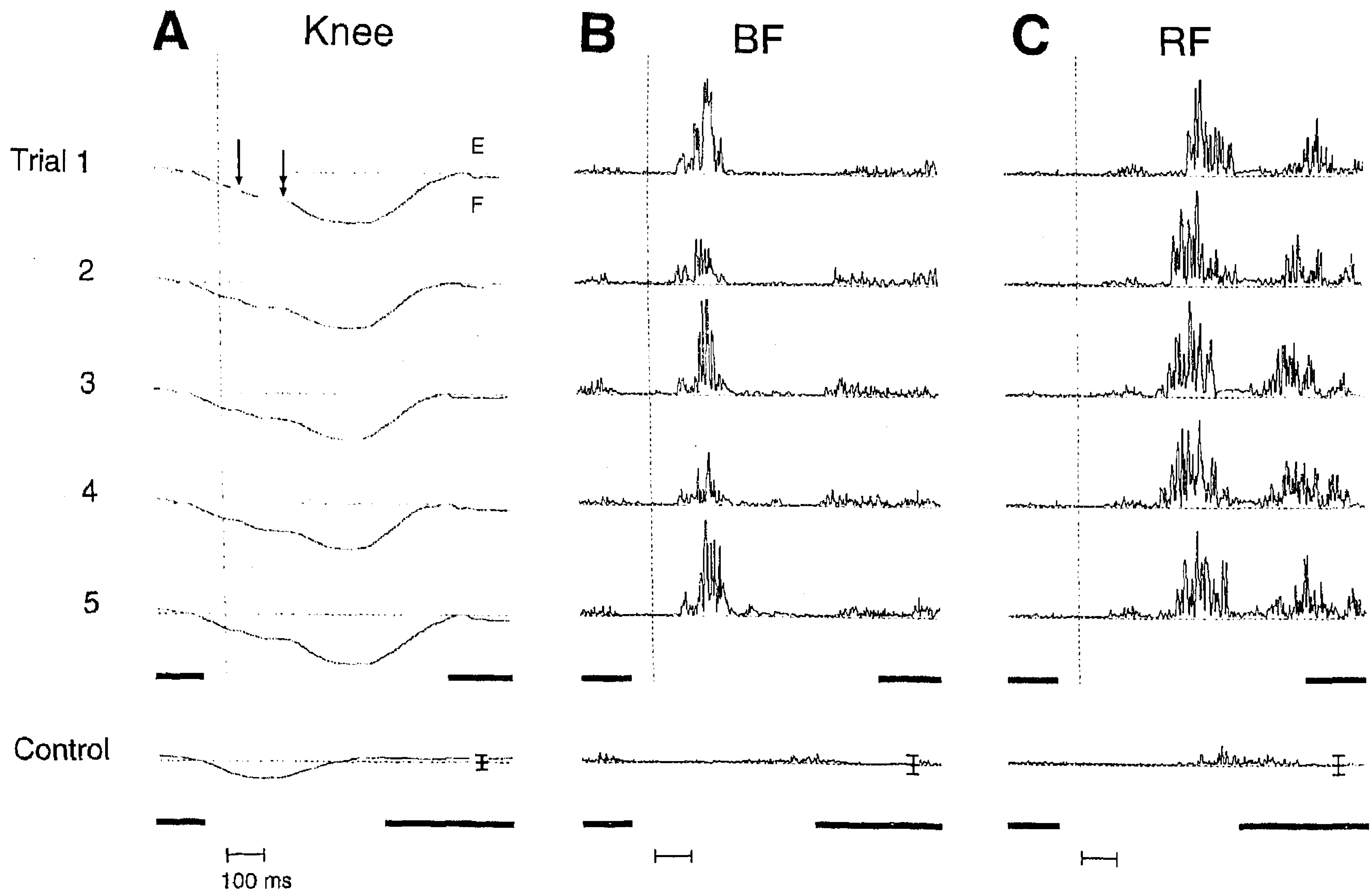

Fig. 4. Reproducibility of the responses after perturbations by the obstacle with a height of 4.5 cm in early swing. Traces 1–5 show individual trials with the knee angle (A), BF (B), and RF (C) responses of 1 subject (other subject than in Fig. 2). Lowest trace shows the activity of a control trial. Dashed vertical lines: time of perturbation. Single arrow indicates first deviation from the knee angle in the unperturbed swing (mechanical effect); double arrow indicates extra flexion due to muscle activity. E: extension, F: flexion. Black bars: stance phases of perturbation trials ($n = 5$), and control trial ($n = 1$). Cal.: 1 mV (EMG), 30° (knee).

subject shown in Fig. 4. This was not significantly different from the step cycle duration as measured in a separate experiment without perturbations (mean: 468 ms; SD: 17 ms; $n = 10$). The angle changes and EMG activity observed during the control step cycles in the stumble experiment were also not different from those seen during the separate experiment without perturbations.

In all subjects, stumble responses were evoked in early swing. The reproducibility of the responses within the other 4 subjects was similar to the one described in Fig. 4. All subjects exhibited large knee flexions to lift the foot over the obstacle. For the 5 subjects, the mean latencies of the earliest BF and RF responses varied from 60 to 76 ms and 72 to 96 ms, respectively. The large amplitude responses in the BF always preceded the large amplitude responses in the RF.

The perturbations in the subject shown in Fig. 4 occurred on average 59 ms after toe-off (SD: 11 ms; $n = 5$), which is on average 12% (SD: 2%) of the duration of unperturbed swing. The foot contact with the obstacle (as measured with the pressure-sensitive strip) lasted on average 167 ms (SD: 18 ms).

Altogether 75 perturbations were presented to the 5 subjects in the early swing phase. The foot missed the obstacle 14 times. Hence, 61 times successful stumbling was evoked. However, 15 trials were excluded from further analysis since the proper timing of the perturbation in these trials failed. Therefore, in 61% of all perturbations successful stumbling reactions were evoked in a specific phase of the step cycle. For all subjects, the collision occurred on average at 14% (SD: 4%) of the total duration of the unperturbed swing. All these perturbations occurred in a period from 30 to 106 ms after toe-off.

Several factors may be responsible for variations in the timing of the perturbation. First, variations in the timing of the normal step cycle occur. For example, the duration of the unperturbed swing phase for the subject shown in Fig. 4 varied between 465 and 503 ms (mean: 488 ms; SD: 14 ms; $n = 10$).

Second, anterior–posterior movements of the subject on the treadmill prior to the perturbation could endanger proper timing of the perturbation. On the basis of the video pictures we estimated that the subject shown in Fig. 4 moved maximally 5 cm in anterior or posterior direction from his starting position. A displacement of 1 cm can cause a change of 9 ms in the timing of the perturbation, since the treadmill velocity was 4 km/h.

Thirdly, fluctuations in the duration of the period between the trigger to the electromagnet and the time at which the obstacle lands on the treadmill could occur. To quantify these variations and to check whether the functioning of the electromagnet was affected by the duration of the 'power on' period, the following procedures were carried out. First, the mean time interval between the trigger and the landing of the obstacle on the treadmill was measured. This interval was 325 ms, and the SD was 11 ms ($n = 58$). After this first control experiment, the electromagnet remained activated holding the obstacle for half an hour (similar to the durations of the actual experiments). Then the same control experiment was repeated. In this second control experiment, the mean duration of the period between trigger and landing was 329 ms (SD: 11 ms; $n = 58$). The range of all intervals measured in the two control experiments was 300–356 ms. We concluded that the 'power on' period did not affect the delay between trigger and landing of the obstacle within the duration of the experiments.

4. Discussion

In this study it was shown that it is possible to successfully reproduce unexpected perturbations during walking on a treadmill. The stumble responses as measured from the EMG and gonio signals were reproducible within subjects when perturbations were caused by identical obstacles in the same part of the swing phase. The variation in the timing of the perturbation of the analyzed trials was small (SD: 4% of duration of unperturbed swing) and therefore it was possible to study stumbling reactions reliably in well-defined phases of the step cycle.

Perturbations by movable obstacles can occur in real life by stumbling over loose objects (e.g., a stone, a book or a piece of wood). The obstacle was sometimes lifted along with the foot. Hence, the height to which the foot must be lifted to clear the obstacle not only depended on the height of the obstacle, but also on the extent of lifting the obstacle. Therefore, the foot must be lifted higher to clear the obstacle than in a situation, in which the obstacle can not move. However, the early responses are reactions to the initial perturbation, which is always the same for different trials (despite the small variation in the timing of the perturbation).

Obstacles permanently attached to the treadmill were used by Drew (1993) to study the voluntary modifications of gait needed to step over the obstacles in cats. If such a set-up would be used in humans to perturb the swing phase unexpectedly, a few disadvantages would occur. Using an obstacle fixed to the treadmill, it is not possible to apply a perturbation at a specific time in the step cycle. Furthermore, the perturbations succeed each other at short regular intervals. In that case subjects would be able to predict the time of perturbation and, in addition, would not have enough time to regain their normal walking pattern between two perturbations.

Our experimental set-up had some impact on the realistic character of the perturbation and the reactions. The use of a treadmill possibly influences the stumbling movements because the walking velocity is fixed. Nevertheless, subjects had the possibility to move forwards and backwards to a certain extent and in this way they could change their walking velocity. From the video recordings it appeared that during the stumbling the subjects did not try to stay at the same place on the treadmill, but regained their position after the stumbling reaction was finished.

The glasses did not allow vision of the obstacles or feet prior to the perturbation. The instruction to the subjects was to look to the wall in front of them. They kept doing so even following the perturbation. We think that in real life the tendency to look down after a perturbation can be expected when people walk on an uneven terrain. In that case it is necessary to look down to place the foot at a 'safe' place. In our laboratory setting however, subjects know the surface structure and the size of the treadmill belt.

After perturbations in early swing, increased knee flexion to lift the foot over the obstacle was observed. This is in agreement with the flexor component of the swing limb in response to perturbations in early swing ($\approx 20\%$ of the swing phase) as described by Eng et al. (1994) as part of the so-called 'elevating strategy'.

The mean latencies of the responses observed in the ipsilateral BF (76 ms) and RF (76 ms) are similar to the latencies observed for responses in other muscles as have been described in prior studies in which mechanical perturbations were caused during human locomotion. Responses evoked by decelerating the treadmill had latencies of 65–75 ms in the tibialis anterior (Berger et al., 1984). Dietz et al. (1986) described responses with latencies of 65–70 ms in the ipsilateral gastrocnemius after mechanical perturbation during the swing phase by a holding impulse. Ghori and Luckwill (1989) found responses in the RF with a mean latency of 82 ms after a resistance applied during swing on a treadmill. Eng et al. (1994) described mean response latencies of about 75 ms (their Fig. 3A) in the BF after perturbations in early swing, which were caused by obstacles (height: 8 cm) on a walkway. The RF responses described by Eng et al. (1994) occurred with a mean latency of 115 ms (their Fig. 3A). These longer latencies as compared to ours (76 ms) are possibly due to the use of a different technique to cause unexpected perturbations during swing. Flexibility of the perturbing object and duration of foot contact with the object could play a role.

On average, the duration of the swing phase in the described subject was prolonged by 196 ms after the perturbation in early swing. A lengthened swing phase (≈ 80 ms) was also reported by Dietz et al. (1986) after applying a momentary resistance of 80 ms above the ankle joint at the onset of the swing phase in walking humans. For perturbations in early swing, Eng et al. (1994) described a mean swing phase prolongation of 97 ms, and they also showed an example of a swing phase which was increased by about 180 ms (their Fig. 5).

In this study it was for the first time that obstacles were used to cause perturbations during human walking on a treadmill. The technique is easy to implement in any experimental setting with a treadmill, since basically only an electromagnet, an obstacle, and a computer program for triggering the magnet are needed. The use of a treadmill makes it easy to control a number of variables such as speed of locomotion and timing of perturbation as has been shown in studies with electrical stimulation (Duysens et al., 1990, 1992; Tax et al., 1995). The results of the presented stumble method (in which both cutaneous and proprioceptive afferents are activated) can be easily compared with the results obtained in these latter studies, which selectively stimulated cutaneous afferents. In fact, in studies with tactile electrical stimulation of cutaneous afferents from the foot, similar latencies were found for responses in the ipsilateral BF and RF (≈ 80 ms) during human running (Tax et al., 1995). Hence, it is quite possible that some of the presently described responses with mean latencies of 60–96 ms use basically the same pathways as those described in this study. As in experiments with electrical stimulation, it is possible to study the phase-related changes in responses. Perturbations with different timings in the swing phase can easily be randomized within an experiment. Not only the timing, but also the height of the obstacle can easily be manipulated in this experimental setting. In fact, successful results were also obtained with obstacle heights of 6.5 and 8.5 cm (unpublished observations).

In conclusion, this method provides a new opportunity to qualitatively and quantitatively study corrective responses to unexpected mechanical perturbations during human walking on a treadmill.

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